Earth Surface Processes and Landforms
Earth Surf. Process. Landforms **23**, 731–750 (1998)

MODELLING FAILURE MECHANISMS TO EXPLAIN ROCK SLOPE CHANGE ALONG THE ISLE OF PURBECK COAST, UK

ROBERT J. ALLISON* AND OWEN G. KIMBER
Department of Geography, University of Durham, Science Laboratories, Durham, DH1 3LE, UK

Received 2 December 1996; Revised 15 October 1997; Accepted 1 December 1997

ABSTRACT

Results are presented of distinct element computer modelling used to examine rates and mechanisms of change in rock slopes and cliffs, where material intact properties determine process and form but the most significant controls are the joint pattern and cross-joint properties. The modelling approach does not appear to have been used before in a geomorphological context and provides an alternative approach for examining cliff development. Field and laboratory data have been collected for the Portland Limestone outcrop of the Isle of Purbeck, central southern England. The Portland Limestone is a hard, shelly, crystalline sediment of the Upper Jurassic. It has a regular discontinuity pattern throughout the outcrop in Purbeck. While joint orientation remains relatively constant, bedding changes from horizontal to vertical, a consequence of the Purbeck Monocline. There are resulting implications for spatial variations in rock slope evolution. The modelling exercise enhances previous knowledge on rock failure mechanisms and slope development along the Purbeck coast and demonstrates its potential in research where landforms are developed in lithified, jointed rock masses. © 1998 John Wiley & Sons, Ltd.

KEY WORDS: rock slopes; rock mass properties; distinct element analysis; Universal Distinct Element Code; Isle of Purbeck, Dorset.

INTRODUCTION

Despite the use of models in geomorphology to understand slope process (e.g. Graham, 1984; Anderson and Richards, 1987; Ahnert, 1994, 1996), much of the work concentrates on soft sediments and soils. The focus on weakly bonded earth materials, which have undergone little or no lithification, at least in part reflects the availability of modelling techniques developed in parallel disciplines (Michalowski, 1995a, b; Duncan, 1996) which are subsequently applicable to geomorphological problems. The focus on soft earth materials is also a function of problems inherent in attempting to study failure mechanisms in fractured rock masses such as the infrequent spatial and temporal nature of rockfall activity from a cliff face and the near impossibility of instrumenting a site destined to undergo failure which is nearly always sudden, rapid and short lived (Whalley, 1984; Hall, 1996; Allison, in press). Some of the differences between instability in soft sediments and lithified, jointed rock masses can be used to illustrate the point. Site monitoring of soft earth materials is often at locations where failure has already occurred, the moving mass is sliding across a boundary shear surface and data are used either to undertake some form of back analysis and identify the conditions which triggered the initial movement or to determine variable associations which are likely to promote further activity. In jointed materials failure usually results in the complete removal of slipped debris and discontinuities within the rock mass form the boundary shear surface. Site monitoring either before movement starts or after the initial failure, in order to collect data for back analysis, is not a realistic goal. Moreover, while first-time slips in soft earth materials are likely to stabilize and reactivate as controlling conditions change, failures in jointed rock masses are frequently discrete events with long time periods between one rockfall and the next at the same point. Research which attempts to explain mechanisms of failure in rock slopes and cliff development in lithified, fracture-pervasive outcrops, where the rock mass is controlled by discontinuities and intact material properties, therefore lags behind understanding of other landslide types and processes.

* Correspondence to: R. J. Allison, Department of Geography, University of Durham, Science Laboratories, Durham, DH1 3LE, UK.

CCC 0197-9337/98/080731–20 $17.50

A pattern of evolving work can be identified. There are studies which attempt to quantify volumes of falling material either by catching moving blocks (Rapp, 1960; Luckman, 1976; Whalley, 1984) or using photogrammetry (Blagorolin and Tsvetkov, 1972) or from repeated mapping of cliffs to establish the distribution and size of failure scars as indications of where falls have occurred (e.g. May and Heeps, 1985; Allison, 1989). None of the approaches helps to explain how controls on instability interact to produce failure or what the precise nature of the failure mechanism is. One step beyond largely morphometric studies of spatial occurrence and event size are semi-quantitative rock mass classification studies which have been developed in engineering (Barton *et al*., 1974; Geological Society Engineering Group Working Party, 1977) and modified for use in geomorphology (e.g. Selby, 1980; Moon, 1984; Abrahams and Parsons, 1987) to determine spatial associations between slope form and rock mass properties (Allison and Goudie, 1990). It is possible to establish whether profiles are in equilibrium with controlling rock properties (Selby, 1987). More recently rock mass strength (RMS) classifications have been used as an indicator of *in situ* stresses and slope development (Augustinus, 1995a, b). Other studies (e.g. Allison *et al*., 1993; Allison, 1996a) have looked in detail at quantitative, geotechnical parameters such as rock stress/strain behaviour and links with spatial variations in slope form. What all of the approaches lack is the synthesis that rigorous, quantitative, slope models have provided for soft sediments.

The aim of the research presented here is to address some of the issues of rock slope failure and development through the use of distinct element computer modelling as a technique for improving understanding of rock slope form and development, based on the synthesis of geomorphological and rock mass geotechnical data. The use of distinct element modelling for examining natural landforms in fractured rock is limited. Attempts to quantify parameters associated with failure have concentrated on either specific aspects of individual events, such as run-out distance (Hutchinson, 1971), or the characteristics of large rock avalanches. There has been little detailed geomorphological investigation of cliff form or slope profile development relative to the displacement of rock mass block sequences.

In assessing the stability of a jointed rock system, the choice of various different modelling approaches would seem to lie at some point between two extremes (Cundall, 1971). At one end of the spectrum are limit equilibrium calculations where a factor of safety (*Fs*) is determined for a particular set of conditions (Nash, 1987; Williams *et al*., 1994; Lunardi *et al*., 1994; Goodman, 1980). Parameters measured in the field and laboratory are used to determine stability conditions at a particular point in time or the changes in controlling variables required to cross the threshold from a stable to an unstable state. Alternatively, finite element analyses can be undertaken (Zienkiewicz, 1977; Hall, 1996). A mesh is defined based on material properties. Changes to the rock mass are determined by assuming the response to loading can be approximated by considering a cross-section made up of deformable elements connected at the corners or nodes. The technique can be time-consuming and complex depending on material property homogeneity, the extent to which a mesh has multiple nodes, and changes in boundary conditions. Examples include the study of cliffs near to Niagara Falls, Canada (Lee, 1978), and isolated mountain peaks in Antarctica (Augustinus and Selby, 1990).

In developing understanding of slope instability, the rates and mechanisms of change and evolution in form, there is an ever-present need to elucidate and understand the links between material properties, earth surface processes and morphology (Allison, 1996a, in press). Geomorphological studies often consider earth material characteristics but there is seldom a detailed synthesis of their control on process activity or landform genesis. An advantage of the modelling approach used here is that it provides a rigorous, quantitative framework for combining the three types of data and meets the geomorphological goal of improving understanding of a complex and poorly understood aspect of landform development through the application of rigorous geomechanical methods, based on the principles of stress distribution within a rock mass. A degree of simplicity is maintained, which includes the input of important material properties and easily interpreted output (Kimber, 1996). Results for both spatial trends between sites and temporal patterns at one location can be conveniently analyzed. As a consequence, while it is recognized that there are aspects of the approach which might be improved in terms of how the model reflects the real world environment, the technique provides a significant step in improving understanding. It links, in a controlled and effectively constrained manner, morphological, process and rock mass geotechnical variables to improve understanding beyond previous methodologies.

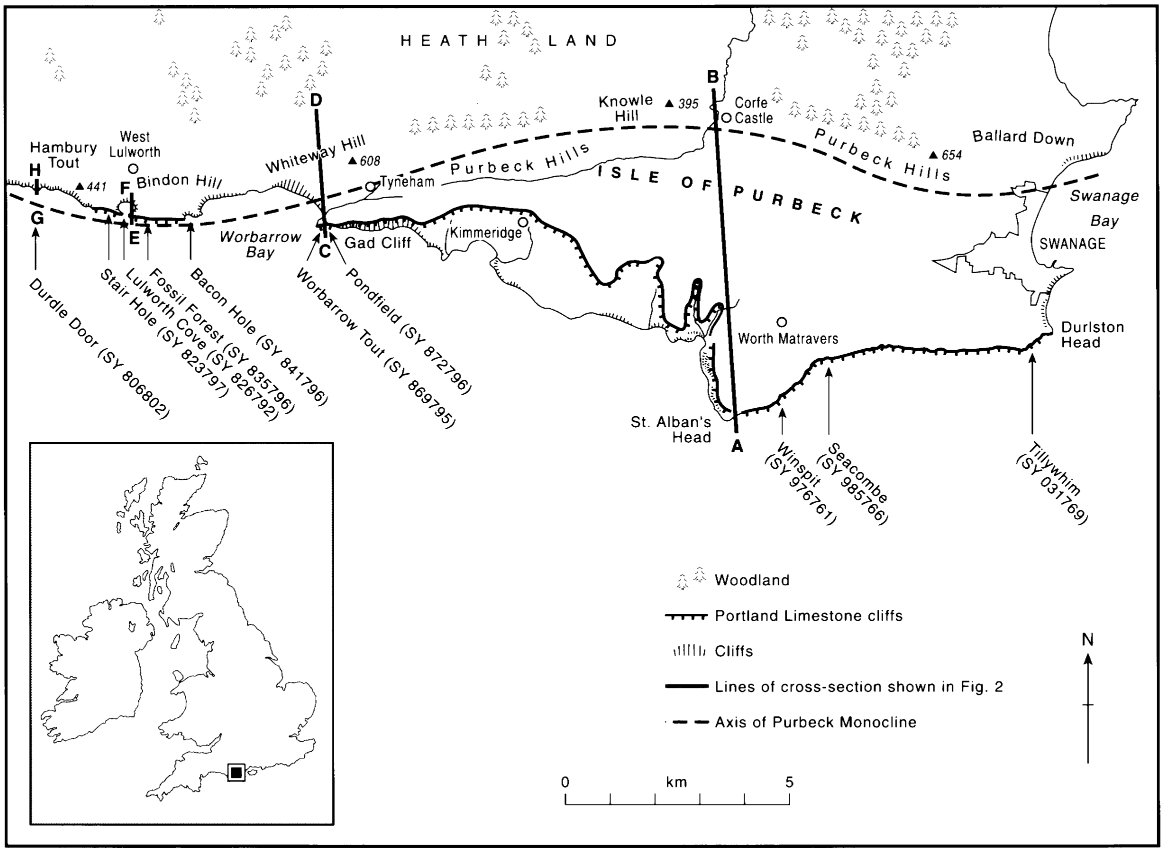

Figure 1. Location of the study area and sampling points used in the study

THE STUDY AREA AND FIELD DATA COLLECTION

The coastline between the Isle of Portland (SY 690720) and Swanage Bay (SZ 035795), part of the Isle of Purbeck (Figure 1), comprises a suite of landforms which are extensively documented and regarded as classic features (Brunsden and Goudie, 1981; Allison, 1986). The morphology of the coast is very much a consequence of juxtaposed sedimentary rocks which have differing resistance to weathering and erosion. Soft materials include the Wealden Beds, Upper Greensand and Gault from the Cretaceous which are prone to landslide activity (Allison and Brunsden, 1990). In contrast, the Cretaceous Chalk and the Upper Jurassic Portland Limestone form resistant ramparts to erosion, with associated coastal cliffs reaching altitudes of 150 m at Bat's Head, 120 m at Gad Cliff and 108 m at St Alban's Head. The Isle of Purbeck is traversed by the Purbeck Monocline, which runs approximately east–west and slightly oblique to the coast. The Monocline swings inland at the eastern end of Worbarrow Bay and passes out to sea in the vicinity of Swanage Bay. Much of the gently dipping southerly limb of the structure has been removed by marine action although the dip of the Isle of Portland at around 2° south reflects the regional structural control. Due to the oblique trend of the Monocline relative to the southerly facing coastline and variation in the orientation of the fold axis, different parts of the flat-lying central section and steeply dipping northerly limb of the structure are exposed in the coastal cliffs. A comparison of geological cross-sections between Durdle Door and St Alban's Head (Figure 2) illustrates the point.

In the east at St Alban's Head (Figure 2, section A–B), the coastal cliffs have developed in the central section of the Monocline. The stratigraphy is horizontally bedded, with Kimmeridge Clay outcropping at the base of the

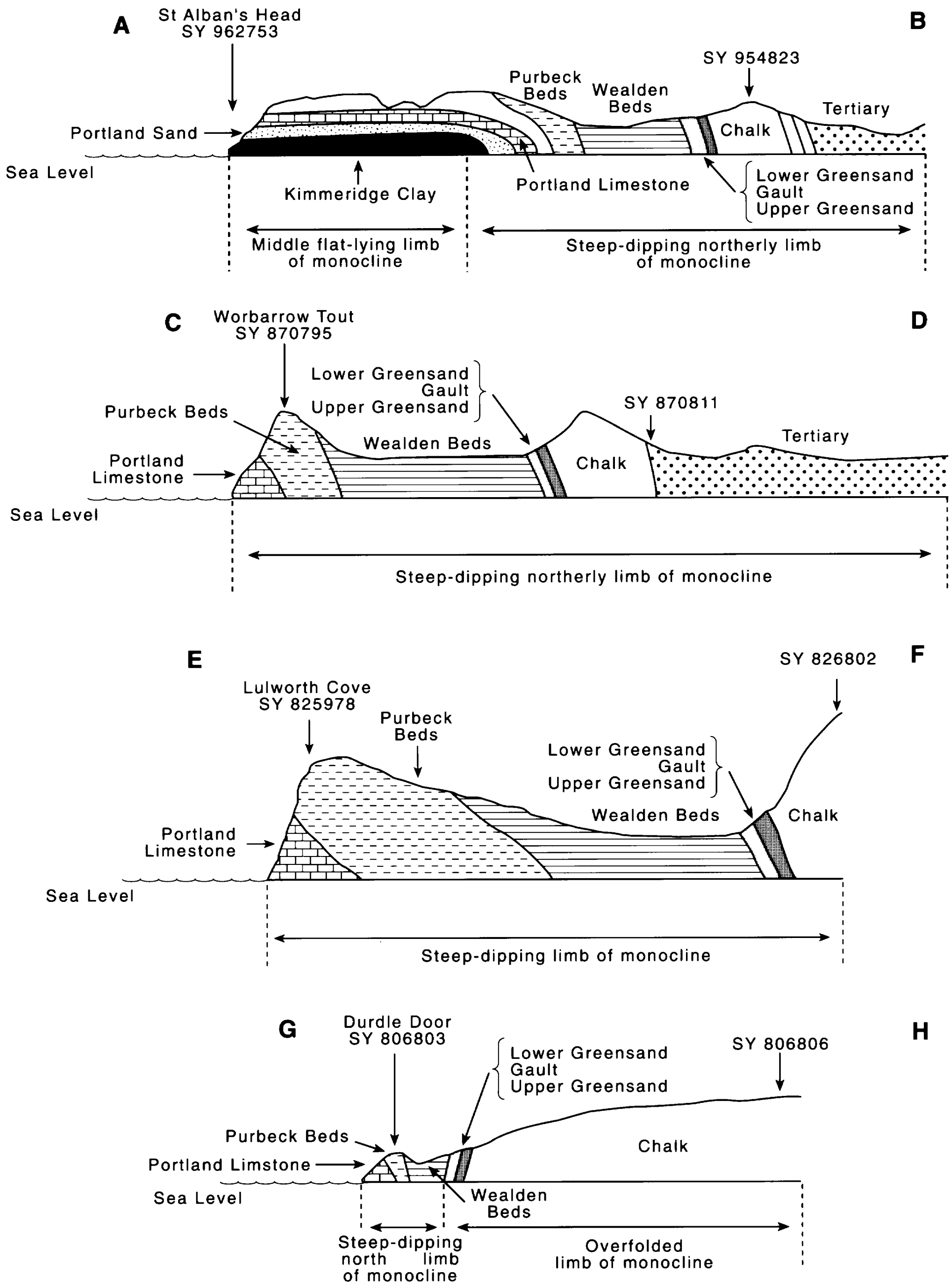

Figure 2. Geological cross-sections highlighting the control of the Purbeck Monocline on the juxtaposition of stratigraphic units along the coast: A–B St Alban's Head; C–D Worbarrow Bay; E–F Lulworth Cove; G–H Durdle Door

cliff, capped by Portland Sand and Portland Limestone. At the eastern end of Worbarrow Bay (Figure 2, section C–D) the dip of bedding at the coast is inclined at an angle of 25° north. Kimmeridge Clay and Portland Sand are not exposed at the base of the cliff. Most of the rock outcrop is in Portland Limestone although the Purbeck Beds appear in places towards the top of the cliff profile. The dip of bedding a Lulworth Cove (Figure 2, section E–F) is 36° north, reflecting the increasing influence of the steeply inclined limb of the Monocline. Neither

Kimmeridge Clay nor Portland Sand is exposed at sea-level; Portland Limestone forms the entire cliff rampart at the coast and the Purbeck Beds crop out behind the Limestone. The most westerly point where the influence of the Purbeck Monocline is clearly seen in the cliffs is at the Durdle Promontory (Figure 2, section G–H), where bedding dips steeply to the north, except where over-folding in the Lower Greensand, Gault, Upper Greensand and Chalk has turned bedding towards the south. Large exposures of the Portland Limestone outcrop but most of the stratigraphic units between the Portland and the Chalk have been removed by marine processes. As the structure swings from horizontal in the east to near-vertical in the west, the stratigraphic units thin. As a consequence, the distance between the Chalk and Portland Limestone approaches 4·5 km at Swanage Bay but is little more than 50 m at Durdle Door (Arkell, 1947).

Of relevance to the study are the Portland Limestone cliffs between Durdle Door and Durlston Head (Strahan, 1898; Cox, 1929; Arkell, 1933; Hounsell, 1952). Where the Portland Limestone is absent, either marine processes have breached the outcrop or rivers have incised the Limestone (Steers, 1964; Jones *et al.*, 1983). The lower part of Gad Cliff is strewn with Limestone boulders. Portland Sand and Kimmeridge Clay below the Limestone at sea-level promote rockfall activity in a similar manner to that reported on the Isle of Portland (Brunsden *et al.*, 1996). From the eastern end of Gad Cliff the Portland Limestone swings inland, returning to the coastal cliffs at Chapman's Pool, remaining high in the cliff around much of St Alban's Head and reappearing at sea-level towards Winspit. From Winspit eastwards the coastal cliffs are almost entirely of Portland Limestone. At Durlston Head the rock unit plunges below sea-level.

Ten locations were identified in Portland Limestone cliffs along the coast for the collection of field data and rock samples for laboratory analysis (Figure 1). The sample points reflect the changing control which the Purbeck Monocline has on the coastal cliff discontinuity pattern. At each place the height of the cliff crest above sea-level and the mean slope angle of the free face were recorded. *In situ* rock blocks were removed from the cliff along intersecting discontinuities; their orientation was noted and they were returned to the laboratory for material property analysis. A joint survey was undertaken at each location, noting the dip and strike of joints and bedding planes. Data were collected by laying tapes parallel and at 90° to the strike of bedding, with recordings taken along the base-line. The orientation of each discontinuity bisecting the tape over a set distance, determined by the complexity of the site fracture pattern, was logged. A minimum of 150 readings was taken along each transect. Care was taken to collect a sufficiently large number of readings to avoid sample bias (Terzaghi, 1965; Hoek and Bray, 1981; Priest and Hudson, 1981; Hudson and Priest, 1981). Discontinuities vary in orientation along their length. A representative surface needs to reflect the mean dip and strike directions (Terzaghi, 1965). The number of readings taken for each fracture set must fairly reflect its overall dominance and control within the cliff profile. The guidelines proposed by Oda (1988) were followed to minimize error. It is pertinent to note that the analysis and modelling of rock slopes and cliffs in geomorphology is often data-limited for unambiguous interpretations, since it is frequently impossible on purely logistical grounds to obtain relevant data for an entire rock mass (Starfield and Cundall, 1988). The field sites used in this study have cliff sections which are representative of surrounding conditions and sufficient access to allow accurate and adequate data collection.

THE MODELLING APPROACH

Recent examples from the coastline of central southern England where models have been used include a study of mudslide stability using planar slide analysis (Allison, 1986) and the application of Bishop's method of slices at Bindon, part of the Axmouth to Lyme Regis National Nature Reserve (Pitts, 1981, 1983). There are problems in applying Limit Equilibrium techniques to jointed, lithified materials. It may be impossible to ascertain the mode of failure prior to occurrence and it is difficult to take into account material properties. Parameters may change as a result of progressive or gradual movement at the start of a more rapid event. Finite Element methods overcome many of the problems associated with Limit Equilibrium techniques but issues still arise with sequences of jointed rock blocks. It is difficult for the element system to alter its geometry as a result of displacements across joints.

Models developed in geomorphology to examine aspects of slope development include the work of Ahnert (Ahnert, 1987, 1988, 1996), which considers temporal aspects of ground surface lowering and slope

development, Kirby's study of thresholds and instability in stream head hollows (Kirkby, 1994), and elucidation of links between hillslope hydrology and ground movements (Anderson and Brooks, 1996). Reviews of recent research (e.g. Allison, 1994, 1996b) indicate that the majority of stability modelling in geomorphology is focused on explaining the behaviour of soft regolith materials. Understanding the behaviour of material such as limestone and chalk has concentrated largely on cliff retreat rates and profile changes (May and Heeps, 1985), although more recently rock strength and fracture patterns have been related to both rock cliff retreat rates (Allison, 1989) and slope form (Nicholas and Dixon, 1986; Allison *et al*., 1993). Site-specific simulation models have occasionally been developed. An example is multi-block simulation modelling to evaluate cliff failure risk in Carbonaceous and Old Red Sandstone series along the Welsh coast (Williams *et al*., 1994). Parallel to this has been the development of rock mass strength classifications (Selby, 1980; Moon, 1984; Abrahams and Parsons, 1987) and their application to landforms such as bornhardts (Selby, 1982a), inselbergs (Selby, 1982b) and the form and asymmetry of glaciated valleys (Augustinus, 1995a, b). In some cases, research has extended into the application of fine element techniques in fracture-dominated materials (Selby *et al*., 1988).

The modelling approach used in this study is the distinct element method, which is ideal for studying large rock block displacements and the evolution of slope profiles which have varied form and steepness (Cundall, 1971). There are some important differences between a continuum, implicit approach based on the finite element methods, which is increasingly common in geomorphological studies, and discrete, explicit methods. In implicit models, a single, effective medium is designed to deform on the average like an assemblage of joints and blocks (Senseny and Simons, 1994). Implicit models therefore trade computation efficiency for lack of detail in modelling the behaviour of jointed rock masses. Discrete models account for interactions between individual rock blocks but the associated increase in detail required greater computational power. The code, known as the Universal Distinct Element Code (UDEC), allows the determination of individual rock block geometries within a cliff face, stress patterns and distributions, displacements of varied size and type including rotations (Pritchard and Savigny, 1990, 1991) and movement vectors. UDEC can account for factors such as block deformation, fracture generation, fluid pressure and permeability. The technique is particularly successful in the modelling of rock slopes in engineering geology which contain prominent discontinuity sets (Hsu and Nelson, 1990). Examples include the stability analysis of undermined cliffs in the Loire valley (Homand-Etienne *et al*., 1990), defining toppling mechanisms and controlling failure surfaces (Ishida *et al*., 1987; Pritchard and Savigny, 1991), the assessment of mining-induced subsidence in Australia (O'Connor and Dowding, 1990) and tunnel stability (Makurat *et al*., 1990). Importantly, UDEC can represent the discontinuous deformation of jointed rock and many recent studies have been used to verify the link between real-world problems and UDEC as an appropriate analytical solution (Brady *et al*., 1990; Choi and Coultard, 1990; Lemos, 1990; Senseny and Simons, 1994).

UDEC is a command-driven program which is executable from an input file and has three distinguishing features. First, interactions between rock blocks are governed by cross-joint parameters which act through corner and edge contacts and control the degree of friction between elements within a rock mass. Intact material properties determine the stiffness of a block and hence boundary controls between individual units. Second, discontinuities are regarded as boundary interactions between blocks. Joint behaviour is prescribed for the interactions. Third, the method utilizes an explicit time-stepping algorithm, which allows large displacements. The latter point is important geomorphologically because there is no limit to the maximum displacement of blocks in the model. A variety of movement mechanisms, including sliding, rotation, toppling and progressive failure, can be replicated. Any block can touch any other block and a model-defined rock block system fails by that mode with the lowest stability. For every iteration of the model, the shear force at every contact point may be tested to determine whether or not it exceeds the conditions required for failure. The model permits the study of many controlling variables in natural slope and rock cliff systems, including cross-joint parameters, loading conditions and undercutting. All of the factors may be varied independently of each other. Since the model is time-marched, it may be run through sequences of iterations to examine change. The time step is sufficiently small that either the velocity or the acceleration in the model are constant. The model may be interrupted at any point within a pre-defined number of cycles to check stability conditions, vectors of movement, the nature of balanced *vs* unbalanced forces and changes to slope form.

Table I. Characteristics of the cliff profiles and fracture patterns recorded at sites along the Isle of Purbeck coast

	Durdle Door	Stair Hole	Lulworth Cove	Fossil Forest	Bacon Hole	Worbarrow Tout	Pondfield	Winspit	Seacombe	Tillywhim
Ordnance Survey grid reference	SY 806802	SY 823797	SY 826797	SY 835796	SY 841796	SY 869795	SY 872796	SY 976761	SY 985766	SZ 031769
Cliff height above m.s.l. (m)	30	55	28	43	37	58	99	43	38	28
Cliff length below m.s.l. (m)	7	7	7	6	11	3	2	4	5	4
Cliff free-face angle (x°)	74	71	68	66	58	66	80	85	90	90
Dip of bedding (x°)	52	38	36	25	25	37	36	0	0	0
Strike of bedding (x°)	101	95	90	92	63	63	74			
Corner angle of basement block (x°)	53	76	96	83	84	85	85	90	90	90
Orientation of cliff line (x° from N)	90	79	80	90	90	84	87	42	76	57
Schmidt hammer ‘r’-value	29	27	38	33	31	46	32	31	28	34
Joint set I: dip $\angle$ E°	86	83	76	85	75	76	80	88	88	85
Joint set I: strike	9	15	13	174	21	168	5	9	4	172
Joint set II: dip $\angle$ S°	42	45	54	68	65	61	77	80	80	85
Joint set II: strike	80	91	83	86	85	82	76	89	84	96
Joint set III: dip $\angle$ SE°	66	60	66	58	68	70	60	84	73	65
Joint set III: strike	52	42	64	47	41	65	60	49	60	90
Joint set IV: dip $\angle$ SW°	53	52	71	78	69	71	82	84	82	90
Joint set IV: strike	152	149	136	130	143	142	152	133	147	132

MODEL INPUT PARAMETERS

Prior to modelling, preliminary data analysis was undertaken to identify similarities and differences between the sites based on important rock mass parameters. Characteristics of the cliff profile and discontinuity pattern at each site are noted in Table I. A discriminating factor is the discontinuity pattern, which can be used to group the sites into four sets. At one extreme is Durdle Door, where bedding dips at 52° north. At the other end of the spectrum are the sites of Seacombe, Winspit and Tillywhim, where bedding is horizontal. The coastal cliffs are formed in the central, flat-lying section of the Purbeck Monocline. The sites of Bacon Hole and Fossil Forest are characterized by bedding which dips at 25° north. Outcrops at Stair Hole, Lulworth Cove, Worbarrow Bay and Pondfield have an angle of dip to bedding between 36° north and 38° north. Equal-area stereographic projections (Hoek and Bray, 1981; Priest, 1985) highlight mean bedding characteristics at all ten sites along the coast (Figure 3a) and indicate a small joint set variability at the four sites of Winspit, Fossil Forest, Lulworth Cove and Durdle Door (Figure 3b). Detailed examination of individual rock outcrops, at the entrance to Lulworth Cove for example, indicates that for the major joint sets identified from the stereonets there is considerable continuity back into the rock mass. It tends to be the randomly distributed joints which are variable and discontinuous.

Representative sites for modelling can also be identified by considering the mechanical properties of the Portland Limestone. A Hoek triaxial Cell (Vickers, 1983) was used to determine the failure characteristics of rock samples collected at each field site. Non-destructive ultrasonic tests (Allison, 1987, 1988) were also completed (Table II) to obtain values for Dynamic Young’s Modulus and Poisson’s Ratio. If the results of the triaxial tests are examined by plotting the shear stress at failure against the confining stress, the sites can be clustered into groups (Figure 4). Material from Durdle Door is the most competent, intact Limestone. The rocks from Durdle Door are also from the most steeply dipping part of the Monocline and there may be a structural control, just as the Chalk hereabouts displays tectonic hardening (Melville and Freshney, 1982). At the other end of the spectrum is the Portland Limestone from Winspit. A third group comprises Limestone at Fossil Forest, Bacon Hole, Pondfield, Seacombe and Tillywhim, with the remaining locations of Stair Hole, Lulworth and Worbarrow Tout forming a fourth subset.

Based on the analysis of rock discontinuity and mechanical properties, four sites can be selected which are representative of the changing rock mass properties along the Isle of Purbeck coast. Durdle Door has a steep bedding, material with a high yield strength, a free-face slope angle of 74° and a cliff height of 29·5 m. The strength and discontinuity parameters single the site out and warrant more detailed analysis. Lulworth Cove has bedding which dips at 36° north, intermediate yield strength when compared with other sites, a free-face slope

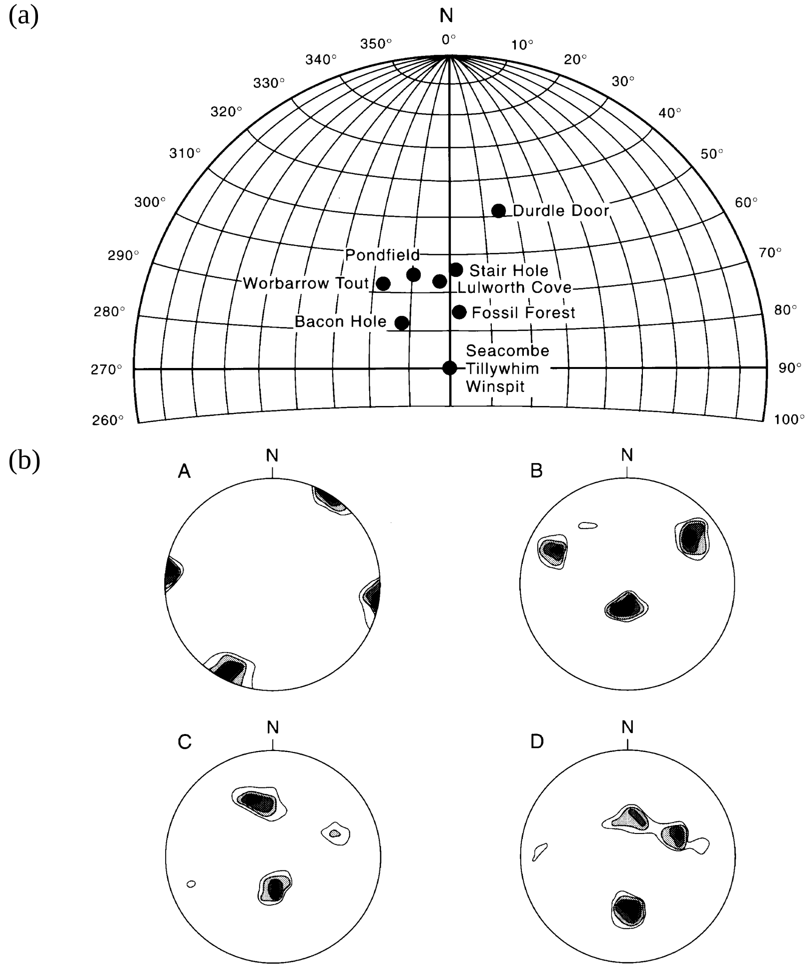

Figure 3. Stereographic projections illustrating the discontinuity characteristics of field sites. (a) Poles plotted to show the dip of bedding for each site. (b) Contoured nets for sites used in the modelling.

angle of 68° and a cliff height of 27·5 m. The bedding angle is characteristic of Portland outcrops which are relatively steeply dipping. Fossil Forest has bedding which dips at 25° north, intermediate yield strength at failure, a free-face slope angle of 66° and a cliff height of 43 m. It is one of a cluster of sites with similar characteristics. Winspit has bedding which is horizontal, a low yield strength at failure, a free-face slope angle of 85° and a cliff height of 43 m. The site is typical of coastal cliffs at the eastern end of Purbeck.

Relevant parameters were defined in appropriate format as model input (Table III), which includes rock mass block geometry and boundary conditions on the one hand and material properties for the intact rock and rock joints on the other. The start point for each model mesh is the current cliff profile; in other words, a simple but fair representation of the real world as the basis for comparing between-site future change. Alternative model start points were considered, such as a vertical cliff face with removal of toe-slope rock blocks to generate failure. To maintain accuracy and, as far as possible, links between real-world measurements and defined model mesh networks, all parameters used in the model are measured values either in the field or in the laboratory.

Individual rocks were defined as rigid units, since all of the cliffs have a relatively low altitude, small gravitational stress and a relatively high material strength, with failure usually taking place along discontinuities rather than through the material. With a gravitational component of $9{\cdot}81\,\mathrm{m\,s^{-2}}$, stresses were set to act vertically through the model to simulate the overburden weight based on cliff height. Meshes were defined to represent the discontinuity pattern at 90° to the trend of each cliff free-face. A computer program was

Table II. Results from triaxial Hoek Cell tests and ultrasonic tests on rock samples collected at sites to examine the mechanical properties of the Portland Limestone

	Porosity (%)	Bulk density ($kg\,m^{-3}$)	Dynamic Young's module ($kN\,mm^{-2}$)	Bulk modulus (GPa)	Shear modulus (GPa)	Yield stress (σ_3=15 MPa) (MPa)	Yield stress (σ_3=30 MPa) (MPa)
Durdle Door	3·59	2570	59·23	41·13	23·5	280	373
Stair Hole	1·80	3190	51·35	35·66	20·38	251	317
Lulworth Cove	2·51	2580	61·9	42·99	24·56	240	299
Fossil Forest	7·19	2390	53·09	36·87	21·07	173	271
Bacon Hole	6·66	2420	46·63	32·38	18·5	226	262
Worbarrow Tout	2·31	2790	58·16	40·39	23·08	259	307
Pondfield	9·96	2350	43·72	30·36	17·35	204	255
Winspit	10·12	2260	39·78	27·63	15·78	153	188
Seacombe	7·69	2390	40·82	28·35	16·2	204	255
Tillywhim	9·86	2350	56·97	39·56	22·61	205	267

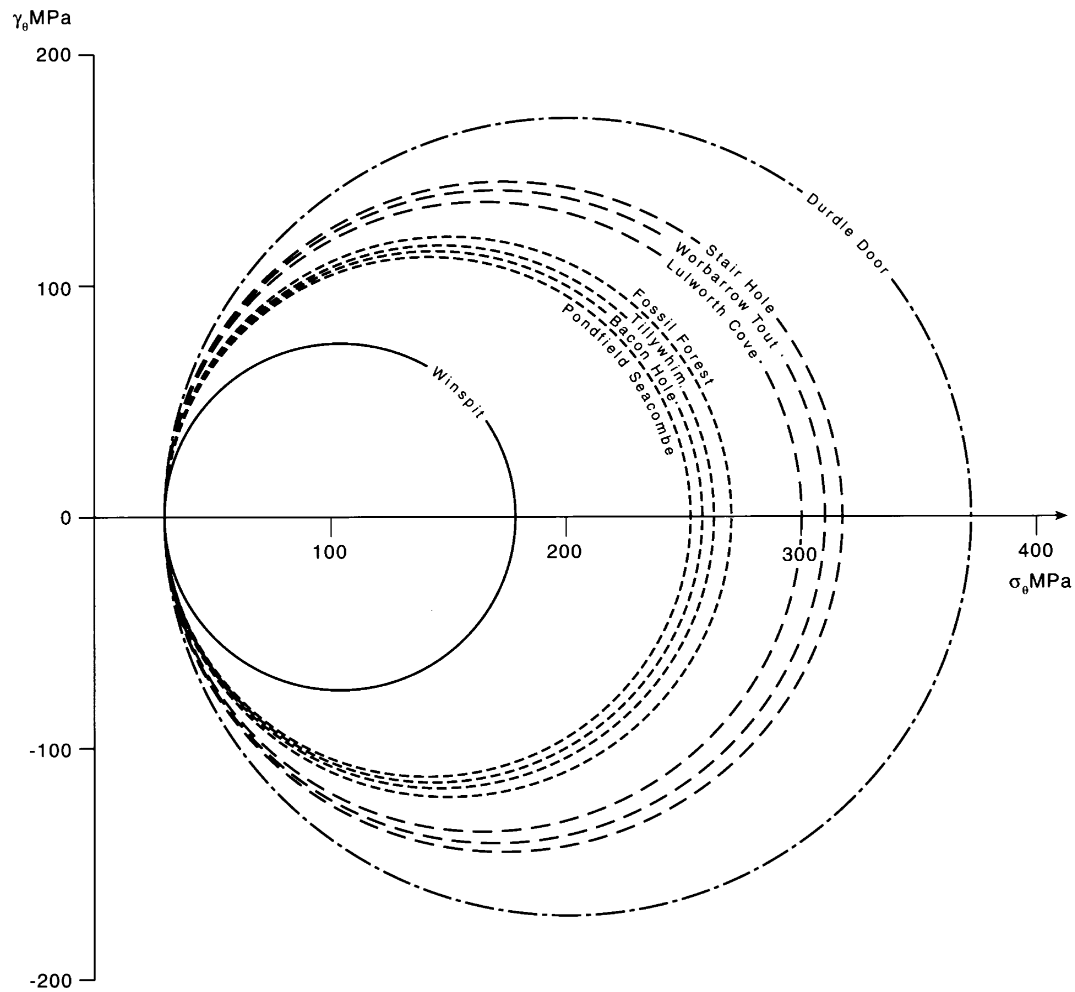

Figure 4. Changes in rock strength for the Portland Limestone along the Isle of Purbeck coast, illustrated by plotting compressive stress at failure (γ_θ) against confining pressure (σ_θ) as Mohr circles

Table III. Model input parameters

	Winspit	Fossil Forest	Lulworth Cove	Durdle Door
Free-face height above m.s.l. (m)	43	43	28	30
Free-face height below m.s.l. (m)	4	6	7	7
Free-face angle (x°)	85	66	68	74
UDEC mesh bearing at 90° to coast	317	358	005	355
Joint set A: angle (x°)	90	56	–40	–42
Joint set A: spacing (m)	2·88	2·25	6·00	1·8
Joint set B: angle (x°)	–67	62	48	35
Joint set B: spacing (m)	2·46	2·25	1·8	1·8
Joint set C: angle (x°)			32	21
Joint set C: spacing (m)			1·8	1·8
Bedding: angle (x°)	0	25	36	52
Bedding: spacing (m)	3·48	3·0	2·4	2·4
Bulk density ($kg\,m^{-3}$)	2260	2390	2580	2570
Bulk modulus (GPa)	27·6	36·8	43·0	41·1
Shear modulus (GPa)	15·8	20·8	24·6	23·5
Joint normal stiffness ($GPa\,m^{-1}$)	20·0	20·0	20·0	20·0
Joint shear stiffness ($GPa\,m^{-1}$)	4·0	4·0	4·0	4·0
Joint friction angle (x°)	36·0	36·0	36·0	36·0

Negative signs for joint angle data indicate dips down and positive signs dips up from horizontal

written (Kimber, 1996) to convert field dip and strike measurements into the appropriate orientation for mesh construction. At the beginning of each model run, boundaries were fixed to allow for block settling and model consolidation. The purpose of the consolidation phase is to allow an equilibrium condition to be reached before boundary conditions are freed to permit rock mass failure. For each of the four sites, equilibrium was achieved at 6000 iterations of the model, with an exponential reduction of the unbalanced forces towards zero. Once an equilibrium condition had been reached, that side of each model representing the coastal cliff was released to allow displacement of blocks along the cliff edge. Mesh images were staged at every 2000 cycles.

An additional consideration relative to data collection along coastal cliffs in the influence of marine processes which are likely to affect cliff stability. Factors include the force of breaking waves (Allsop *et al*., 1996) against the rock face and consequent joint cleft water pressure (Bandis, 1990), the permanent immersion of the lower part of the cliff beneath sea-level, variations in rates of joint weathering between the toe and crest of the cliff particularly where tidal oscillations result in the repeated exposure and submergence of *in situ* rock and accelerated rates of post-failure block removal from the base of a slope.

Although not directly measured in the field, parameters such as the force of breaking waves can be accounted for by defining appropriate values for the pressure of water within joints (Gale, 1990), both at different points vertically up the cliff face and relative to the horizontal distance into the rock mass from the daylighting face. While breaking wave water pressures will have some influence on bare exposed rock faces, it will be the joint water pressure implications which primarily determine the dislodgement of blocks, failure patterns and slope profile changes (Engelder and Lacazette, 1990). Similarly, if necessary, the effects of submerging the lower part of the cliff profile can be defined at the start of model runs by ascribing appropriate geotechnical values for the intact rock and by defining cross-joint properties which reflect cavity saturation and a two-phase rock/fluid medium rather than a three-phase rock/fluid/air system. Once defined at the start of modelling, the variables can be varied at points during sequential time-steps to account for changes such as rises and falls in sea-level.

There are other factors which are likely to exert control on cliff change but which it is presently difficult to define accurately within the model. One example is the rate of removal of blocks which have become detached from the cliff and rest as a talus pile at the toe of the slope. The model has the capacity to account for this characteristic in two ways. First, it is possible to split blocks by adding discontinuities. The effect is to change the geometry of the slipped rock block mass and disturb the balance between individual blocks, thereby generating further displacements. The second method for accounting for post-failure talus block weathering and erosion is the deletion and hence removal of blocks from the mesh. Block deletion can be done either by eliminating a block from the mesh in its entirety at one point in the time sequence or by reducing the size of a block. For the purposes of the simple modelling exercise reported here these variables were held constant for a number of reasons. The key model inputs, both morphologically and geotechnically, will collectively have the

most significant control on rock cliff stability and change. It is possible, with reasonable accuracy, to constrain other model parameters to real-world scenarios whereas those relating to post-failure block disintegration are much more difficult to deal with (Kimber *et al*., in press).

In summary, model inputs subdivide into a number of groups. There is essential numeric information which includes details of cliff morphology, discontinuity characteristics, rock block properties and cross-joint parameters. There are variables which can be defined at the start of model runs and either held constant throughout time-steps or varied to account for site-specific environmental controls such as marine processes. There are parameters which add much complexity to the modelling process and, to permit spatial and temporal comparisons, were assumed to be constant both within and between sites, although work is presently in progress to develop this component of the model.

RESULTS

The results of model runs are illustrated by sequences of plots for each of the representative field sites which follow a shift from east to west along the Isle of Purbeck coast from Winspit to Fossil Forest, Lulworth Cove and Durdle Door. In each plot sequence, direct comparison is possible between sites since the number of cycles is the same at each representative stage of the modelling process. One additional plot is presented for Durdle Door due to the nature of the slope failures which have been generated by the model. Hard copy can be produced after each model cycle but in practice rockfall activity and cliff profile changes are best examined on-screen first and illustrative material selected for discussion. At each of the sites the first plot in the sequence (Figures 5A, 6A, 7A and 8A) represents conditions once equilibrium has been established prior to the initiation of failure. Differences in the morphological characteristics of the cliff and changes in the fracture pattern are clearly visible. The best contrast is between the meshes for Winspit and Durdle Door. At Winspit (Figure 5A) joints are widely spaced, resulting in large blocks of rock. Bedding is horizontal with a regular fracture pattern and almost vertical cliff face. At Durdle Door (Figure 8A) bedding dips steeply to the north, the overall fracture pattern is close-spaced and the consequence is a dense network of small blocks of rock. Some of the blocks are rectangular in shape while others are triangular due to an intermittent joint set within the rock mass, seen and measured in the field as discontinuous fractures within the outcrop.

The last plot in each sequence represents equilibrium site conditions once rockfall activity has ceased. Each of the diagrams (Figures 5D, 6D, 7D and 8E) represents $1{\cdot}6\times10^6$ model cycles, which for the most complex of the discontinuity meshes required a total processing time of approximately 10 days. By the end of each model run the number of slipped blocks at the toe of a slope is less than the total originally present in the cliff face before failure because blocks occasionally fall out of the model. Activity at Fossil Forest is a case in point (Figure 6C) and can be considered the equivalent of run-out distances which extend well beyond the base of the slope or rocks which bounce away from the free face during a fall. Two further plots are presented in each model sequence, the first after 96 000 cycles (Figures 5B, 6B, 7B and 8C) and the second after 742 147 cycles (Figures 5C, 6C, 7C and 8D). Both stages were selected because they illustrate some of the key variations in activity within and between the sites. The second and third plots in each sequence have scaled velocity vector arrows plotted for those blocks which are moving. The orientation of the arrow reflects the direction of movement and its length the velocity. One further plot at Durdle Door after 24 000 cycles (Figure 8B) reflects the movement pattern at this site, which is more rapid than at the other locations.

At Winspit (Figure 5A to 5D) a near-vertical cliff face fails as columns of blocks become detached from the rock slope. Initially the first block column starts to move after 10 900 model cycles. At the top of the cliff the rocks fall vertically, maintaining a relatively constant orientation (Figure 5B). The basal blocks rotate as a consequence of the vertical motion of the overburden and the orientation of the joints controlling failure. Following the initial failure, a block-covered talus slope develops. More significantly, a further three columns begin to move and a stepped cliff profile develops (Figure 5C and 5D). A number of the talus blocks are balanced precariously. This condition would probably be temporary in the field, with weathering and erosion leading to further movement within the failed blocks and the further movement of rock blocks away from the

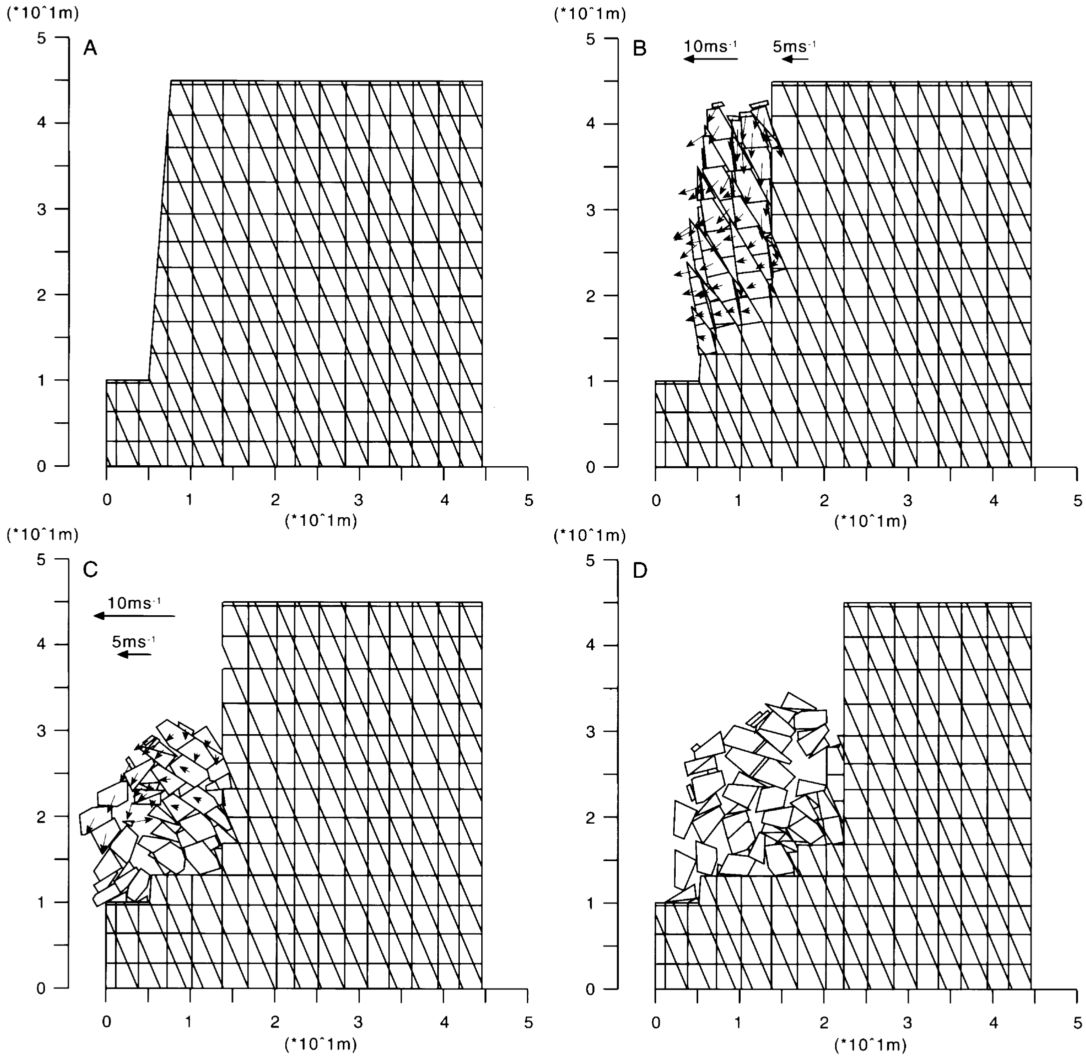

Figure 5. Model of cliff profile development at Winspit (arrows are scaled velocity vectors at the moment in the model run represented by each plot)

cliff face. It also reflects the fact that while the code is good at modelling changes to the cliff, the relative juxtaposition of disconnected blocks is less accurate. The stability of the cliff appears to be episodic, with displaced blocks acting as a buttress to the rock slope and the stress conditions up the cliff face changing through time due to the removal of rock columns. At Fossil Forest the rock slope failure mechanism has changed (Figure 6A to 6D). The initial model conditions (Figure 6A) reflect the field site, with a bench approximately three-quarters of the way up the profile. The velocity vectors show that displacements are by sliding across a critical joint surface in the rock mass (Figure 6B), with very small displacements preceding the main failure which starts after 13 700 model cycles. A number of the displaced blocks disappear from the mesh. After 742 000 cycles (Figure 6C) there are key blocks at the toe of the slope which support the other slipped rocks. One of the block vectors shows that the rock is bounding out and away from the cliff face, illustrating that at the instants where model output has been caught to illustrate the output, most moving blocks will be interacting as a system but some will be responding in a discrete manner. Between this point and the final

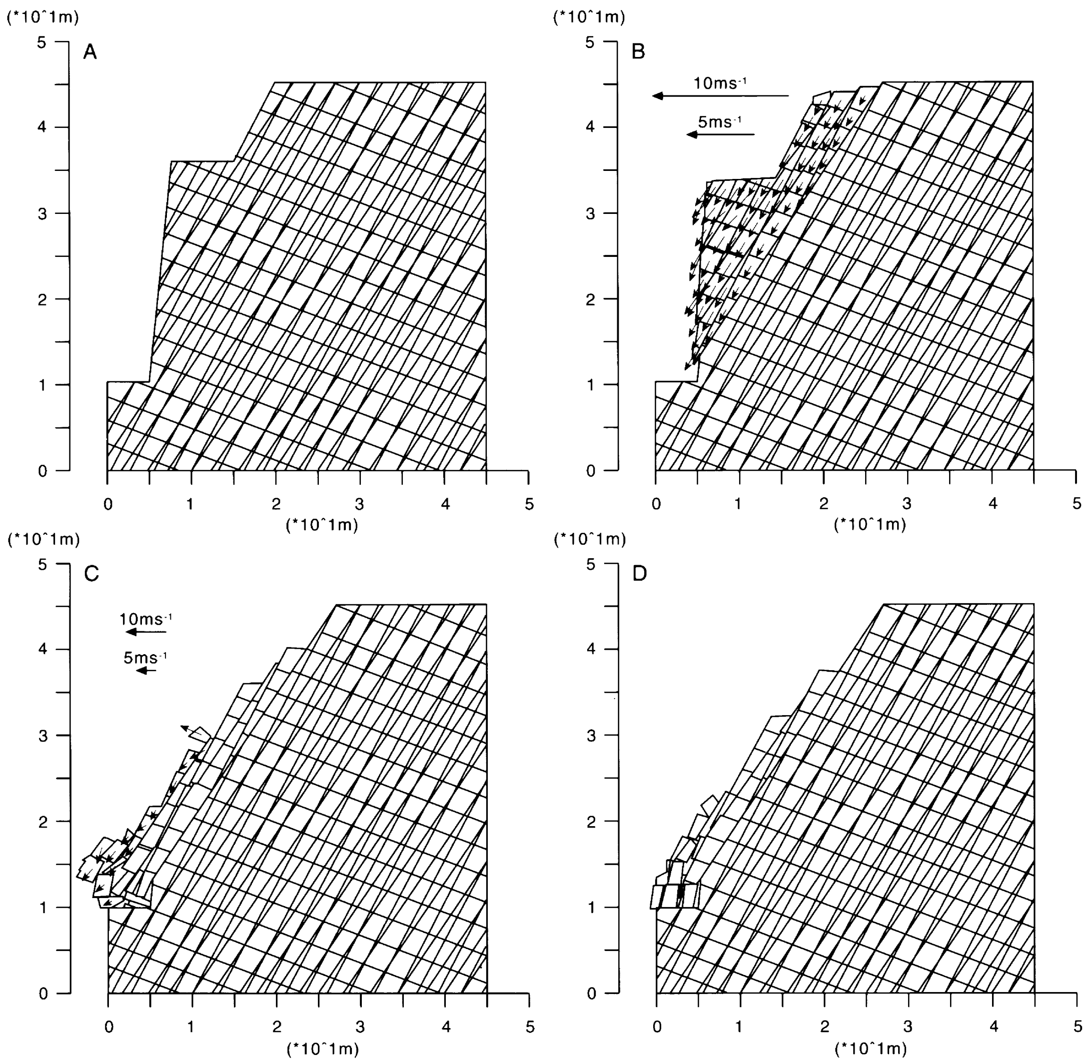

Figure 6. Model of cliff profile development at Fossil Forest (arrows are scaled velocity vectors at the moment in the model run represented by each plot)

iteration of the model (Figure 6D), some of the supporting units are removed and the up-slope material slides vertically over the controlling joint plane. The failure mechanism at Fossil Forest thus appears to be one where an initial displacement takes place and a sequence of rock blocks move over a controlling joint, which subsequently acts as a sliding surface across which further down-slope movements occur. Once the slope has failed the frequency of movement will depend in part on the extent to which key blocks at the toe of the slope act to support the slipped mass and the buttressing effect displaced material has on the *in situ* rock.

At Lulworth Cove (Figure 7A to 7D) the velocity vectors in early model cycles indicate increasing stresses out of the slope. There is evidence that creep is taking place with small relative displacements between individual rock units within the model mesh as the block vectors increase in magnitude. The rapid strain associated with failure commences at 19 700 model cycles. The velocity vectors associated with initial displacements (Figure 7B) highlight different rates of movement across the moving rock mass and displacements to varying depth in from the rock cliff surface. The consequence is a more complex moving mass

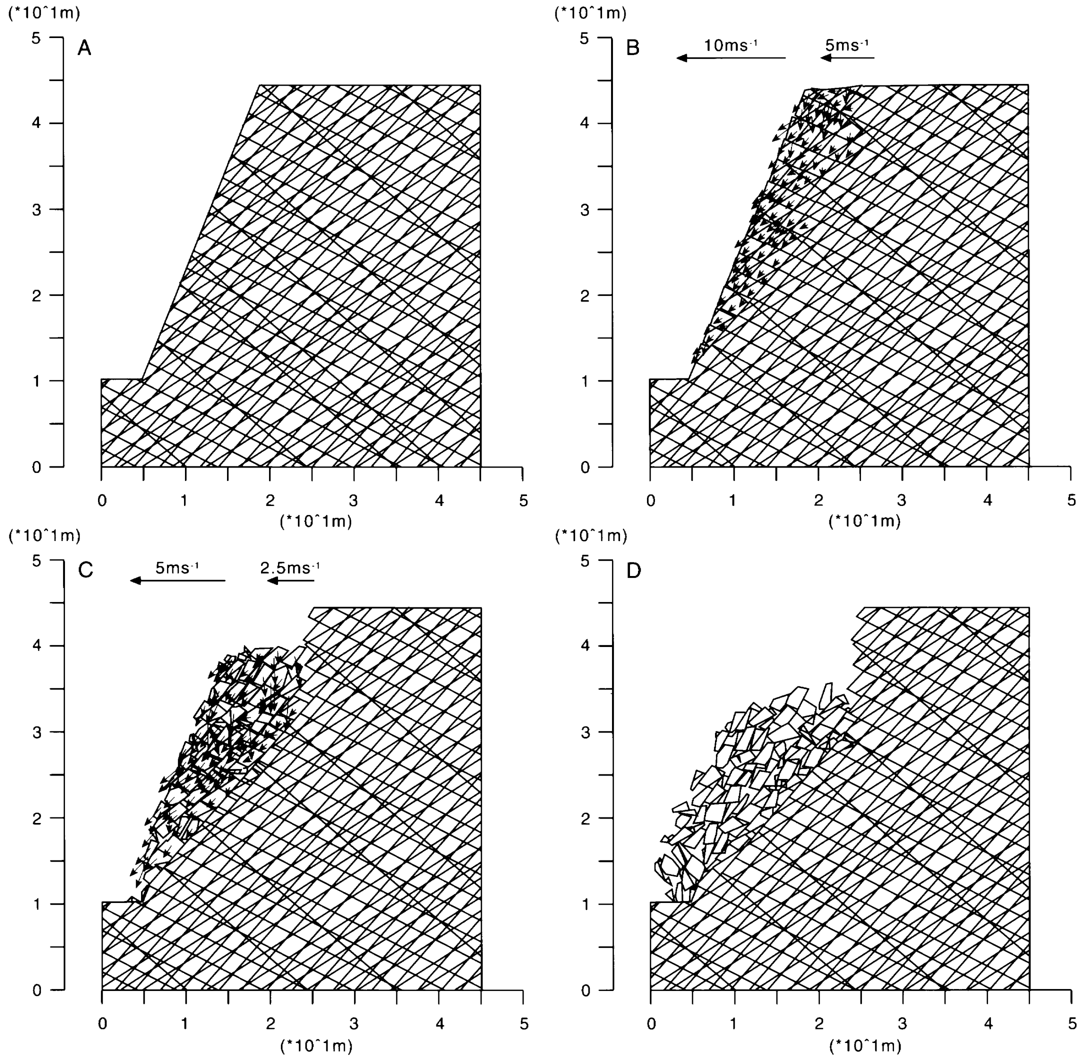

Figure 7. Model of cliff profile development at Lulworth Cove (arrows are scaled velocity vectors at the moment in the model run represented by each plot)

once displacements become significant (Figure 7C) and a more jumbled talus slope at the end of the modelling sequence (Figure 7D). A steep top-slope section develops at Lulworth Cove (Figure 7D), similar to cliff profiles in the field where large overhanging blocks are present. Cross-joint friction appears to be the most likely explanation of this change in slope form towards the top of the profile. The lower slope area stabilizes at a lesser gradient than initially defined in the mesh and with a cover of talus blocks of varying shape and size. At Durdle Door (Figure 8A to 8E) most of the joints are continuous, producing a rectangular block field of varying size but an occasional discontinuous joint is reflected in the random distribution of triangular blocks within the mesh. Following consolidation of the mesh at 6000 cycles (Figure 8A), failure takes place (Figure 8B) through a combined block toppling and sliding mechanism after 9700 model cycles. The result by 96000 cycles is a considerable modification to the original cliff face (Figure 8C). A talus slope has developed with a small number of blocks resting upon it and a steep free-face section. Many of the displaced blocks have been removed from the mesh boundary. At 742147 cycles there have been further failures (Figure 8D). There has been a proportional change in the length of the talus slope and the height of the free face, with the former expanding in length and the latter being reduced.

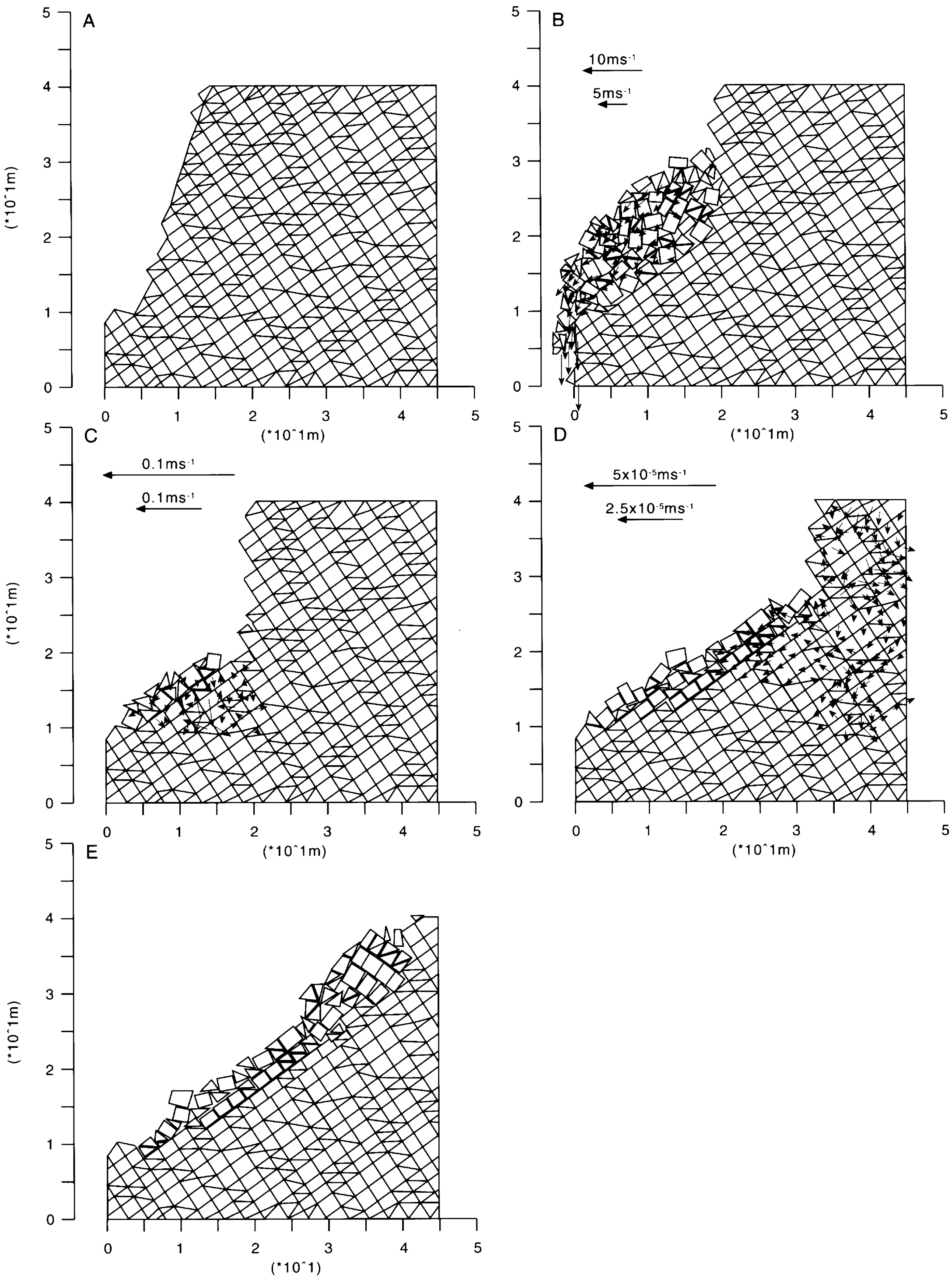

Figure 8. Model of cliff profile development at Durdle Door (arrows are scaled velocity vectors at the moment in the model run represented by each plot)

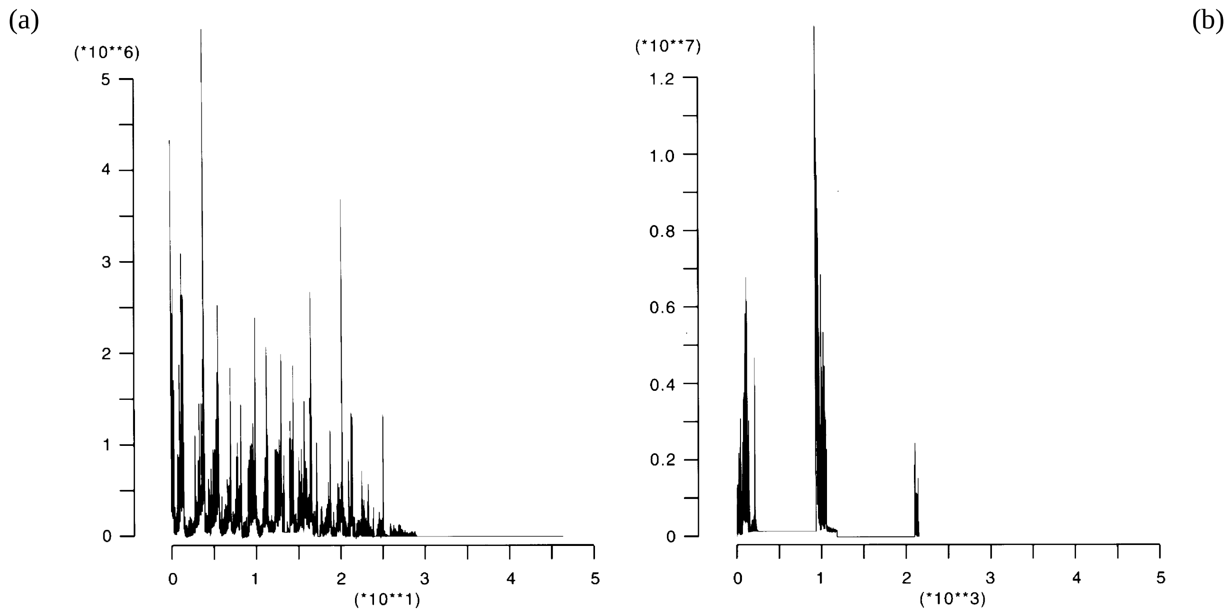

Figure 9. History plots of unbalanced forces during computer model runs at (A) Fossil Forest and (B) Durdle Door

The movement vectors at Durdle Door show considerable complexity. Their dimensions vary tremendously through time, with some as large as $10\,m\,s^{-1}$ and others no greater than $2{\cdot}5\times10^{-5}\,m\,s^{-1}$. The majority of the vectors reflect the gravitational effect on failed blocks. Others point upwards, an indication of stress release as a consequence of overlying material having been removed. It appears that the remainder reflect small between-block movements as the rock mass settles following movement, a point confirmed if large sequences of block plots are viewed in rapid success on the computer screen. By multiple image, rapid output file viewing – a feature of the UDEC code – 'movie' sequences can be generated which explain the majority of the vector magnitudes and directions.

By the final cycle (Figure 8E) the free face at Durdle Door has disappeared and the full slope profile is at a much reduced angle. The mechanism of block displacement also appears to have changed. At the early stages of slope failure, movements are by toppling. In the latter stages of the process there is a composition of sliding towards the toe of the slope and cambering at the crest. Again, the blocks lower down the slope profile appear to be acting as toe slope support. Gradual displacements towards the crest of the slope result in the slow buckling of strata towards the daylighting face. One suggestion is that a key-block (or blocks) exists towards the toe of the slope, which is supporting the material above it. If this were removed, by wave action for example, further movements would occur and the original slope profile would be modified still further.

A small number of the displaced blocks in each of the four model runs appear to have come to rest at improbable positions, further reflecting the accuracy of the technique in establishing cliff profile change but occasional errors in predicting failed block at-rest orientations. The issue is most noticeable in the latter two plots from each model run, emphasizing the chaotic nature of this type of instability (Cundall, 1990) and the difficulties inherent in modelling such a complex process (Gleick, 1987). In reality, the impact velocity of some of the blocks as they strike *in situ* material is likely to generate fracture. The present modelling exercise has not split blocks, to maintain between-site uniformity and control one of the many variables presently being investigated as the technique is refined and further developed.

An interesting result which comes from the modelling exercise is the temporal distribution of balanced and unbalanced forces within each model run. It can be illustrated by comparing two sites, Fossil Forest (Figure 9A) and Durdle Door (Figure 9B). At both sites block movements between the start and end of the model runs occur as pulses of activity, separated by episodes of little or no movement. At Fossil Forest (Figure 9A) activity peaks are separated by periods of quiescence. There is a clear build-up to the activity peak and subsequent sharp

cessation of activity on each occasion. The implication is that rockfall activity occurs at key points through time and that each discrete event commences with the movement of one or two rock blocks. The total volume of falling material quickly increases and then reaches stability in an equally short period of time. At Durdle Door (Figure 9B) the activity peaks are greater and more widely spaced, suggesting that when rock block displacements occur they have the potential to be much larger, more rapid and greater in terms of their morphological effect on the cliff profile. At both sites, stability conditions are eventually reached and no further displacements are recorded.

DISCUSSION AND CONCLUSIONS

Rockfall activity is seldom recorded in the field because it is difficult to monitor specific events due to the short time period over which they occur and the speed of rock displacement. At each of the sites examined here, the outcome of the modelling exercise is somewhat different and this is evident by simply comparing the last diagram in each of the iteration sequences. At Winspit, parallel cliff retreat is occurring. Large blocks of rock skirt the base of the free face. Where the cliffs plunge directly into the sea, the blocks occur below the low-water mark. At other locations, such as Tillywhim, the blocks litter rock benches which have been cut as a consequence of quarrying. The only real difference between the model and reality is the relative juxtaposition of the slipped blocks. The large open spaces which exist between slipped blocks at the end of the model run are largely absent in the field, although some do sit at precarious angles – a consequence, it is suggested, of weathering and erosion which have resulted in post- failure displacements in the field which are not yet incorporated within the model.

Similar conclusions can be drawn at Fossil Forest and Lulworth Cove. At Lulworth, the Portland Limestone cliffs plunge directly into the sea. If it were assumed that marine processors act to remove failed blocks, the modelled cliff profile at Lulworth (Figure 7D) would closely mirror the mechanisms of slope development that are seen in the field, with a smaller number of talus rocks at the toe of the slope profile. At Fossil Forest (Figure 6D), cliff profile development in the field is akin to that at Lulworth, with a serrated appearance to the cliff profile rather than a smooth profile due to sliding along critical joint planes which parallel the slope free face. Further work is in progress to examine the difference which may be due to marine processes acting at the toe of the slope. The Durdle Promontory is an isolated block of Portland Limestone with much of the outcrop removed on either side. The results from the model sequence provide an interesting hypothesis for the destruction of the Portland cliff at Durdle Door. The promontory itself appears to be evolving in a manner which closely approximates to the model, with a steep cliff of rocks which appear to be held *in situ* by little more than cross-joint friction. Talus blocks are found at the toe of the slope below mean sea-level. On either side of the Promontory, where the Portland Limestone outcrop has all but disappeared and submerged reefs remain, the end of the model run is a much fairer reflection of field conditions. In other words, it is suggested that the Durdle Promontory will eventually collapse along the lines of the model runs, tending towards the form of the immediately adjacent Portland Limestone reefs.

An important issue in studies where a model is used to predict temporal landform change is the extent to which the results can be related to real time (Thornes and Brunsden, 1977). To what extent can model time-steps be related to elapsed clock time? Many time-marched models developed within a geomorphological context (e.g. Ahnert, 1996) recognize the difficulties inherent in attempting to link results and real time. They recognize the problems and risks involved in ascribing a real-time base to iterative sequences of model steps. Studies where the finite-element method has been used to examine temporal change to natural relief acknowledge that while it is possible to predict change, it remains unrealistic to ascribe a firm time-base to that change (Augustinus and Selby, 1990). It is not one of the aims of this study to establish a real-time base for the model output. Further research is presently in progress at sites on the Colorado Plateau of the United States of America where absolute dates can be obtained to constrain results in this manner. The approach adopted here rather follows that espoused by Ahnert (1994), who suggests that the model results are satisfactory if they account for past landform development and/or make the future development predictable, having identified controlling components and factors so that realistic between-site comparisons become possible.

The key issues here are ones of (i) using the time-step characteristic of the distinct element based UDEC method to examine differences in rates and mechanisms of cliff development, and (ii) establishing that differential rates of cliff profile development at locations along the coast depend on site geomorphological and geotechnical characteristics (Kimber *et al*., in press). Limitations in establishing links between real time and model time, a consequence of the infrequent and spatially discrete nature of rockfall activity, should not detract from the study. As Kirkby (1994) notes with specific reference to hillslope profiles, simulation models provide one of the crucial links between the study of process and the study of landforms, and are an important means of extrapolating short-term process measurements to the long-term evolution of landforms. Improving understanding of rock slope evolution and associated rockfall activity are all too frequently hampered by the difficulties encountered in measuring a process which is spatially discrete and establishing temporal change when landform evolution occurs over long periods – in the context of establishing a field monitoring program, for example. While the issue of ascribing a real time frame to geomorphological change along the Isle of Purbeck coast remains, the results presented here advance understanding beyond other methods such as recording the spatial distribution of rockfall activity (May and Heeps, 1985; Allison, 1989) or using semi-quantitative rock mass strength methods (Selby, 1993).

A further issue, and one present in many geomorphological studies, is the use of two-dimensional data in explaining landform change, essentially a three-dimensional problem (Allison, 1966a; in press). This may, at least in part, explain some of the inconsistencies between slipped blocks. However, the results in terms of the evolving cliff profile do, in many ways, reflect real-world site conditions. The consequence is that the results provide an advance in understanding rockfalls as a particular slope instability mechanism and thereby merit attention. Just as with many other methods developed to elucidate hillslope development (e.g. Ahnert, 1994, 1996), future refinement such as a move from a two-dimensional to a three-dimensional approach will provide continuously improving results.

The main conclusion to be drawn from the study is that the modelling approach presented here can be used to elucidate rates and mechanisms of cliff change in the Portland Limestone outcrop of the Isle of Purbeck coast. As the outcrop is traversed from east to west the rock mass properties alter and as the modelling exercise indicates, the consequences include a change in the failure mechanism, different rates of profile development and variations in slope form.

ACKNOWLEDGEMENTS

Funding for this research has been gratefully received from the University of Durham Research and Initiatives Committee and the Natural Environment Research Council. Professor Denys Brunsden provided valuable advice on linkage between field data and computer model parameters. The authors would like to thank Mr C. Mullaney and Mr M. Scott for supporting requests for assistance with computer hardware and software. The diagrams were prepared with dexterity by staff in the Cartography Unit, Department of Geography, University of Durham. Valuable comments from two referees significantly improved the quality of the final manuscript.

REFERENCES

Abrahams, A. D. and Parsons, A. J. 1987. 'Identification of strength equilibrium rock slopes: further statistical considerations', *Earth Surface Processes and Landforms,* **12**, 631–635.

Ahnert, F. 1987. 'Approaches to dynamic equilibrium in theoretical simulations of slope development', *Earth Surface Processes and Landforms*, **12**, 3–15.

Ahnert, F. 1988. 'Modelling landform change', in Anderson, M. G. (Ed), *Modelling Geomorphological Systems*, John Wiley & Sons, Chichester, 375–400.

Ahnert, F. 1994. 'Randomness in geomorphological process response models', in Kirkby, M. J. (Ed.), *Process Models and Theoretical Geomorphology*, John Wiley & Sons, Chichester, 1–21.

Ahnert, F. 1996. 'The point of modelling geomorphological systems', in McCann, S. B. and Ford, D. C. (Eds), *Geomorphology Sans Frontières*, John wiley & Sons, Chichester, 91–113.

Allison, R. J. 1986. *Mass movements and coastal cliff development of the Isle of Purbeck, Dorset,* Unpublished PhD thesis, University of London.

Allison, R. J. 1987. 'Non-destructive determination of Dynamic Young's Modulus and its relationship with compressive strength, dry density and porosity of sediments, in Jones, M. E. and Preston, R. M. F. (Eds), *Deformation of Sediments and Sedimentary Rocks*, Blackwell, Oxford, 63–70.

Allison, R. J. 1988. 'A non-destructive method for determining rock strength', *Earth Surface Processes and Landforms,* **13**, 729–736.

Allison, R. J. 1989. 'Rates and mechanisms of change in hard rock coastal cliffs', *Zeitschrift für Geomorphologie,* **SB73**, 125–138.

Allison, R. J. 1994. 'Slopes and slope processes', *Progress in Physical Geography,* **18**, 423–433.

Allison, R. J. 1996a. 'Stress and strain in geomorphology', in Mäusbacher, R. and Schulte, A. (Eds), *Readings in Physical Geography*, Springer-Verlages Heidelberg, Heidelberg, 169–187.

Allison, R. J. 1996b. 'Slopes and slope processes', *Progress in Physical Geography,* **20**, 453–465.

Allison, R. J. in press. 'Geomorphological processes: rates, relationships and return intervals', in Marinos, P. G., Koukis, G. C., Tsiambaos, G. C. and Stournaras, G. C. (Eds), *Engineering Geology and the Environment*, Balkema, Rotterdam.

Allison, R. J. and Brunsden, D. 1990. 'Some mudslide movement patterns', *Earth Surface Processes and Landforms,* **15**, 297–311.

Allison, R. J. and Goudie, A. S. 1990. 'The form of rock slopes in tropical limestone and their associations with rock mass strength', *Zeitschrift für Geomorphologie,* **34**, 129–148.

Allison, R. J., Goudie, A. S. and Cox, N. J. 1993. 'Geotechnical properties of rock masses and their control on rates and mechanisms of cliff change', *Geomorphology,* **8**, 1–16.

Allsop, N. W. H. McKenna, J. E., Vicinanza, D. and Whittaker, T. T. J. 1996. *New design methods for wave impact loadings on vertical breakwaters and seawalls*, 25th International Conference on Coastal Engineering, Orlando.

Anderson, M. G. and Brooks, S. M. 1996. 'Hillslope processes: research prospects', in Anderson, M. G. and Brooks, S. M. (Eds), *Advances in Hillslope Processes,* John Wiley & Sons, Chichester, 5–32.

Anderson, M. G. and Richards, K. S. 1987. 'Modelling slope stability: the complimentary nature of geotechnical and geomorphological applications', in Anderson, M. G. and Richards, K. S. (Eds), *Slope Stability: Geotechnical Engineering and Geomorphology*, John Wiley & Sons, Chichester, 1–9.

Arkell, W. J. 1933. *The Jurassic System of Great Britain*, Clarendon Press, Oxford.

Arkell, W. J. 1947. *The geology of the country around Weymouth, Swanage, Corfe and Lulworth. Memoirs of the Geological Survey of Great Britain*, HMSO, London.

Augustinus, P. 1995a. 'Rock mass strength and the stability of some glaciated valley slopes', *Zeitschrift für Geomorphologie,* **39**, 55–68.

Augustinus, P. 1995b: 'Glacial valley cross-profile development: the influence of *in situ* rock stress and rock mass strength, with examples from the Southern Alps, New Zealand', *Geomorphology,* **14**, 87–97.

Augustinus, P. C. and Selby, M. J. 1990. 'Rock slope development in McMurdo Oasis, Antarctica, and implications for interpretations of glacial history', *Geografiska Annaler,* **72A**, 55–62.

Bandis, S. C. 1990. 'Mechanical properties of rock joints', in Barton, N. and Stephansson, O. (Eds), *Rock Joints*, Balkema, Rotterdam, 125–140.

Barton, N., Lien, R. and Lunde, J. 1974. 'Engineering classification of rock masses for the design of tunnel support', *Rock Mechanics,* **6**, 189–236.

Blagovolin, N. S. and Tsvetkov, D. G. 1972. 'The use of ground photogrammetric surveys for studying the dynamics of slopes', in Adams, W. P. and Helleiner, F. (Eds), *International Geography,* University of Toronto Press, Toronto.

Brady, B. H. G., Hsiung, S. H., Chowdhury, A. H. and Philip, J. 1990. 'Verification studies on the UDEC computational model of jointed rock', in Rossmanith, H. P. (Ed.), *Mechanics of Jointed and Faulted Rock*, Balkema, Rotterdam, 551–558.

Brunsden, D. and Goudie, A. S. 1981. *Classic Coastal Landforms of Dorset*, Geographical Association, Sheffield.

Brunsden, D., Coombe, K., Goudie, A. S. and Parker, A. G. 1996. 'The structural geomorphology of the Isle of Portland, southern England', *Proceedings of the Geologists' Association,* **107**, 209–230.

Choi, S. K. and Coultard, M. A. 1990. 'Modelling of jointed rock masses using the distinct element method', in Rossmanith, H. P. (Ed.), *Mechanics of Jointed and Faulted Rock*, Balkema, Rotterdam, 471–477.

Cox, L. R. 1929. 'A synopsis of the Llambellibranchia and Gastropoda of the Portland Beds of England', *Proceedings of the Dorset Natural History and Archaeology Society,* **50**, 130–202.

Cundall, P. A. 1971. 'A computer model for simulating progressive, large-scale movements in blocky rock systems', *Proceedings of the International Symposium on Rock Fractures, Nancy, France,* **II-8**, 1–12.

Cundall, P. A. 1990. 'Numerical modelling of jointed and faulted rock', in Rossmanith, H. P. (Ed.), *Mechanics of Jointed and Faulted Rock*, Balkema, Rotterdam, 11–18.

Duncan, J. D. 1996. 'State of the art: limit equilibrium and finite element analysis of slopes', *Journal of Geotechnical Engineering,* **122**, 577–596.

Engelder, T. and Lacazette, A. 1990. 'Natural hydraulic fracturing', in Barton, N. and Stephansson, O. (Eds), *Rock Joints*, Balkema, Rotterdam, 35–43.

Gale, J. 1990. 'Hydraulic behaviour of rock joints', in Barton, N. and Stephansson, O. (Eds), *Rock Joints*, Balkema, Rotterdam, 351–362.

Geological Society Engineering Group Working Party. 1977. 'The description of rock masses for engineering purposes', *Quarterly Journal of Engineering Geology,* **10**, 355–388.

Gleick, J. 1987. *Chaos: Making a New Science,* Viking, New York.

Goodman, R. E. 1980. 'Block theory and its application', *Géotechnique,* **45**, 383–423.

Graham, 1984. 'Methods of stability analysis', in Brunsden, D. and Prior, D. B. (Eds), *Slope Instability*, John Wiley & Sons, Chichester, 171–215.

Hall, D. B. 1996. 'Modelling failure of natural rock columns', *Geomorphology,* **15**, 123–134.

Hoek, E. and Bray, J. 1981. *Rock Slope Engineering, 2nd edn.* Institute of Mining and Metallurgy, London.

Homand-Etienne, F., Rode, N. and Schwartemann, R. 1990. 'Block modelling of jointed cliffs', in Rossmanith, H. P. (Ed.), *Mechanics of Jointed and Faulted Rock*, Balkema, Rotterdam, 819–825.

Hounsell, S. S. B. 1952. 'Portland and its stone', *Mine Quarry Engineering,* **18**, 107–114.

Hsu, S. C. and Nelson, P. P. 1990. 'Analyses of slopes in jointed weak rock masses using distinct element method', in Rossmanith, H. P. (Ed.), *Mechanics of Jointed and Faulted Rock,* Balkema, Rotterdam, 589–604.

Hudson, J. A. and Priest, S. D. 1981. 'Discontinuity frequency in rock masses', *International Journal of Rock Mechanics and Mining Sciences,* **20**, 73–89.

Hutchinson, J. N. 1971. 'Field and laboratory studies of a fall in Upper Chalk cliffs at Joss Bay, Isle of Thanet', in Parry, R. H. G. (Ed.), *Stress Strain Behaviour of Soils*, Foulis, Henley-on-Thames, 692–706.
Ishida, T., Chigira, M. and Hibino, S. 1987. 'Application of the distinct element method for analysis of toppling observed on a fissured rock slope', *Rock Mechanics and Rock Engineering,* **20**, 277–283.
Jones, M. E., Allison, R. J. and Gilligan, J. 1983, 'On the relationships between geology and coastal landforms in central southern England', *Proceedings of Dorset Natural History and Archaeology Society,* **105**, 107–118.
Kimber, O. G. 1996. *Rates and Mechanisms of Change in Hard Rock Steep Slopes*, Unpublished Graduate Discussion Paper, Department of Geography, University of Durham.
Kimber, O. G., Allison, R. J. and Cox, N. J. in press. 'Mechanisms of failure and slope development in rock masses', *Transactions of the Institute of British Geographers*.
Kirkby, M. J. 1994. 'Thresholds and instability in stream head hollows: a model of magnitude and frequency for wash processes', in Kirkby, M. J. (Ed.), *Process Models and Theoretical Geomorphology*, John Wiley & Sons, Chichester, 295–314.
Lee, C. F. 1978. 'Stress relief and cliff stability at a power station near Niagara Falls', *Engineering Geology,* **12**, 193–204.
Lemos, J. V. 1990. 'A comparison of numerical and physical models of a blocky medium', in Rossmanith, H. P. (Ed.), *Mechanics of Jointed and Faulted Rock*, Balkema, Rotterdam, 509–514.
Luckman, B. H. 1976. 'Rockfalls and rockfall inventory data: some observations from Surprise Valley, Jasper National Park, Canada, *Earth Surface Processes,* **1**, 287–298
Lunardi, P., Froldi, P. and Fonari, E. 1994. 'Rock mechanics investigations for rock slope stability assessment', *International Journal of Rock Mechanics and Mining Sciences & Geomechanical Abstracts*, **31**, 323–345.
Makurat, A., Barton, N. R., Vik, G., Chryssanthakis, P. and Monsen, K. 1990. 'Jointed rock mass modelling' in Barton, N. R. and Stephansson, O. (Eds), *Rock Joints*, Balkema, Rotterdam, 647–656.
May, V. J. and Heeps, C. 1985. 'The nature and rates of change in chalk coastlines', *Zeitschrift für Geomorphologie*, **57**, 81–94.
Melville, R. V. and Freshney, E. C. 1982. *British Regional Geology. The Hampshire Basin and Adjoining Areas*, HMSO, London.
Michalowski, R. L. 1955a. 'Stability of slopes: limit analysis approach', in Hanerberg, W. C. and Anderson, S. A. (Eds), *Clay and Shale Slope Instability*, Geological Society of America, Reviews in Engineering Geology X, Boulder, CO, 51–62.
Michalowski, R. L. 1995b. 'Slope stability analysis: a kinematical approach', *Geotechnique,* **45**, 283–293.
Moon, B. P. 1984. 'Refinement of a technique for determining rock mass strength of geomorphological purposes', *Earth Surface Processes and Landforms,* **9**, 189–193.
Nash, D. F. T. 1987. 'A comparative review of limit equilibrium methods of stability analysis', in Anderson, M. G. and Richards, K. S. (Eds), *Slope Stability: Geotechnical Engineering and Geomorphology,* John Wiley & Sons, Chichester, 11–75.
Nicholas, R. M. and Dixon, J. C. 1986. 'Sandstone scarp form and retreat in the Land of Standing Rocks, Utah', *Zeitschrift für Geomorphologie,* **30**, 167–187.
O'Connor, K. M. and Dowding, C. H. 1990. 'Monitoring and simulation of mining-induced subsidence', in Rossmanith, H. P (Ed.), *Mechanics of Jointed and Faulted Rock*, Balkema, Rotterdam, 781–787.
Oda, M. 1988. 'A method for evaluating the representative elementary volume based on joint survey of rock mass', *Canadian Geotechnical Journal,* **25**, 440–447.
Pitts, J. 1981. *Landslips of the Axmouth – Lyme Regis National Nature Reserve*, Unpublished PhD thesis, University of London.
Pitts, J. 1983. 'Temporal and spatial development of the landslides in the Axmouth – Lyme Regis undercliffs National Nature Reserve', *Earth Surface Processes and Landforms,* **8**, 589–604.
Priest, S. D. 1985. *Hemispherical Projection Methods in Rock Mechanics*, George Allen & Unwin, London.
Priest, S. D. and Hudson, J. A. 1981. 'Estimation of discontinuity spacing and trace length using scan line surveys', *International Journal of Rock Mechanics and Mining Sciences,* **18**, 183–197.
Pritchard, M. A. and Savigny, K. W. 1990. 'Numerical modelling toppling', *Canadian Geotechnical Journal,* **27**, 823–834.
Pritchard, M. A. and Savigny, K. W. 1991. 'The Heather Hill landslide: an example of a large scale toppling failure in a natural slope, *Canadian Geotechnical Journal,* **28**, 823–834.
Rapp, A. 1960. 'Recent development of mountain slopes in Kärkevagge and surroundings', *Geografiksa Annaler,* **42**, 1–158.
Selby, M. J. 1980. 'A rock mass strength classification for geomorphic purposes: with tests from Antarctica and New Zealand', *Zeitschrift für Geomorphologie,* **24**, 31–51.
Selby, M. J. 1982a. 'The form and origin of some bornhardts of the Namib desert', *Zeitschrift für Geomorphologie,* **26**, 1–15.
Selby, M. J. 1982b. 'Rock mass strength and the form of some inselbergs in the central Namib desert', *Earth Surface Processes and Landforms,* **7**, 489–497.
Selby, M. J. 1987. 'Rock slopes', in Anderson, M. G. and Richards, K. S. (Eds), *Slope Instability*, John Wiley & Sons, Chichester, 475–504.
Selby, M. J. 1993. *Hillslope Materials and Processes, 2nd edn,* Oxford University Press, Oxford.
Selby, M. J., Augustinus, P., Moon, V. G. and Stevenson, R. J. 1988. 'Slopes in strong rock masses: modelling and influences of stress distributions and geomechanical properties', in Anderson, M. G. (Ed.), *Modelling Geomorphological Systems*, John Wiley & Sons, Chichester, 341–374.
Senseny, P. E. and Simons, D. A. 1994. 'Comparison of calculational approaches for structural deformation in jointed rock', *International Journal for Numerical and Analytical Methods in Geomechanics,* **18**, 327–344.
Starfield, A. M. and Cundall, P. A. 1988. 'Towards a methodology for rock mechanics modelling', *International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts,* **25**, 99–106.
Steers, J. A. 1964. *The Coastline of England and Wales, 2nd edn,* Cambridge University Press, Cambridge.
Strahan, A. 1898. *Geology of the Isle of Purbeck and Weymouth*, HMSO, London.
Terzaghi, R. D. 1965. 'Sources of error in joint surveys', *Geotechnique,* **15**, 287–304.
Vickers, B. 1983. *Laboratory Work in Soil Mechanics,* Granada, London.
Whalley, W. B. 1984. 'Rockfalls', in Brunsden, D. and Prior, D. B. (Eds), *Slope Instability*, John Wiley & Sons, Chichester, 217–256.
Williams, A. T., Bomboe, P. and Davies, P. 1994. 'Forecasting coastal cliff failure in jointed rocks', *Proceedings 7th International IAEG Congress*, 3029–3032.
Zinekiewicz, O. C. 1977. *The Finite Element Methods, 3rd edn,* McGraw-Hill, London.

